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Assessment of contaminants in California drinking water by region and system size

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Abstract

In this California-wide spatial analysis, a cumulative ranking method and a trend test were used to estimate and compare concentrations of 12 contaminants and two drinking water standard violations by system size and region. The San Joaquin Valley, areas not served by water systems, and small water systems (less than 200 connections) had the highest cumulative rank with many high levels of contaminants. Large systems and the South Coast had the highest levels of disinfection byproducts and industrial contaminants. Based on a trend analysis, violations and concentrations of arsenic and cadmium decreased as system size increased, while industrial contaminant concentrations and disinfection byproducts increased as system size increased ($p < .05$). Although not indicative of violating drinking water standards, this study's results demonstrate where efforts to address specific contaminants can be targeted by region or system type. The results can help elucidate where contaminants may be elevated, from both an individual and multiple-contaminant perspective.

KEYWORDS

California, drinking water, environmental justice, water quality

1 | INTRODUCTION

California residents receive drinking water from a wide variety of sources and distribution systems due to the state's varied geography, topography, and climate. The majority (95%) of the 38 million Californians receive their water from community water systems (CWSs) with different levels of treatment. However, a small fraction of the state's population relies on state small water systems, which are not regulated by the state, or privately operated groundwater wells with little to no treatment (California Senate Office of Research, 2015; State Water Resources Control Board, 2015a). State small water systems have 5–14 service connections and serve no more than 24 people, 60 days out of the year. The presence of chemical and bacterial contamination can reach the water supply through different pathways from both naturally occurring and anthropogenic sources and has the potential to result in widespread exposures and health concerns.

Several studies have documented high levels of drinking water contaminants in some regions of California and the potential adverse health effects from exposures to

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some contaminants (Calderon, 2000). For example, arsenic and uranium are naturally present in soil and rock and are among the most common contaminants detected in California, especially in San Joaquin Valley (SJV) groundwater (Balazs, Morello-Frosch, Hubbard, & Ray, 2012; Thiros, Paul, Bexfield, & Anning, 2015). In the SJV and in other agricultural areas of the state, the application of fertilizer and leaching of animal waste are a major source of groundwater contamination by nitrate (Balazs, Morello-Frosch, Hubbard, & Ray, 2011; Dubrovsky et al., 2010; Lockhart, King, & Harter, 2013). Exposure to drinking water containing arsenic increases the risk of multiple health effects, including cancer (Parvez et al., 2013; Steinmaus et al., 2013), and nitrate in drinking water has been associated with methemoglobinemia in infants, reproductive toxicity, developmental effects, and various cancers (Fan & Steinberg, 1996; Ward, 2005). Industrial sources such as facilities that manufactured perchlorate or used solid rocket fuel have caused significant perchlorate contamination of groundwater contamination (Fram & Belitz, 2011). Low-level perchlorate contamination of drinking water has been associated with abnormal thyroid function in neonates and pregnant women (Brechner, Parkhurst, Humble, Brown, & Herman, 2000; Steinmaus, Miller, & Smith, 2010). Methods commonly used to disinfect water with chemicals such as chlorine before distribution can introduce byproducts such as trihalomethanes (TTHMs), which have been linked to an increased risk of bladder cancer (Cantor et al., 2010; Richardson & Postigo, 2011). In addition to concern regarding the effects of individual contaminants in drinking water, cumulative exposure to multiple compounds may affect health through chronic exposure, even at low levels (Kolpin et al., 2002; Stoiber, Temkin, Andrews, Campbell, & Naidenko, 2019).

The State Water Resources Control Board (SWRCB)'s Division of Drinking Water regulates drinking water quality for a majority of Californians (about 94%). Of these state-regulated public water systems, approximately 97% met state drinking water quality standards in 2014 (State Water Resources Control Board, 2016), meaning that they did not receive violations for contaminant concentrations exceeding the maximum contaminant level (MCL), which is the regulatory concentration set by the SWRCB. The MCL is based on the public health goal (PHG), which is the concentration level of a contaminant that does not pose a significant risk to health, and the feasibility and cost to detect and treat contamination. Even though most CWSs meet MCL standards, more than 3 million Californians were served by CWSs having at least one violation between 2005 and 2013. Many water systems also still strive to meet the PHG to the extent feasible. Small water systems with fewer than 200 service connections (usually households) and, generally, in rural areas, however, tend to have the greatest difficulty meeting drinking water standards in California (State Water Resources Control Board, 2015b).

The characteristics and locations of water systems that are especially vulnerable to contamination and that struggle to meet health-based and regulatory standards and goals are of particular interest to policymakers. Only a few large-scale studies have examined the role of characteristics such as system size, region, or socioeconomic status on the quality of drinking water. National and local studies have evaluated trends in violations and found that smaller and more rural systems tended to have the largest number of MCL violations (Allaire, Wu, & Lall, 2018; Marcillo & Krometis, 2019; Wallsten & Kosec, 2005). Other studies have also observed similar trends for specific contaminants such as nitrate and carcinogenic compounds in small systems (Evans, Campbell, & Naidenko, 2019; Schaider, Swetschinski, Campbell, & Rudel, 2019). In the SJV, low-income, rural, and socioeconomically disadvantaged communities were more vulnerable to MCL violations and generally had higher levels of nitrates and arsenic (Balazs et al., 2011, 2012). A recent report showed that disadvantaged unincorporated communities in this region are mostly served by small CWSs and state small water systems or private wells, with about a quarter of the small CWSs providing water that was out of compliance with state drinking water quality standards (London et al., 2018). In addition, smaller CWSs in California may lack proper infrastructure and the financial capability to treat or find alternative supplies when needed compared with larger CWSs, making smaller CWSs more vulnerable to groundwater contamination (State Water Resources Control Board, 2013). Mobile home park CWSs in California, which tend to be small systems, are more likely to incur an MCL violation compared with other system types (Pierce & Gonzalez, 2007). Also highly vulnerable are the 2 million Californians not receiving water from public water systems but from very small systems (less than 15 connections) or private wells drawing from groundwater. Neither of these sources are monitored or regulated by the state and may be at greatest risk of exposure to multiple contaminants. A national analysis by the U.S. Geological Survey showed that more than 23% of domestic wells sampled had at least one contaminant with a concentration exceeding the MCL (DeSimone, Hamilton, & Gilliom, 2009).

As research on areas outside of CWSs (domestic well users and nonregulated small CWSs) is limited, this study

is one of the first to examine multiple contaminants in these areas along with assessing how contamination varies regionally and by system size. In addition, while some research has focused on CWSs in the SJV, less is known about contaminants that pose problems for water systems across other California regions. This study is one of the first to characterize potential exposure to multiple contaminants by system size and across all California regions for water systems and the first to also include areas outside of public water systems in the analysis. Especially because communities are impacted by different sets of contaminants depending on their geography, identifying contaminant hotspots and trends in all areas and by types of systems will provide a more comprehensive picture of contamination concerns throughout the complex California drinking water network.

It is important to consider the cumulative effects from the combined exposure of multiple pollutants in drinking water in addition to examining exposure to individual pollutants. Vulnerable communities may already be facing multiple stressors from combined sources of environmental pollution from a variety of different sources (Office of Environmental Health Hazard Assessment, 2017a; Stoiber et al., 2019). This study builds upon an assessment of cumulative exposure to drinking water contaminants developed for an environmental justice screening tool called CalEnviroScreen, which identifies California communities impacted by multiple sources of pollution, such as areas with high levels of air pollution or pesticide use, or the presence of hazardous waste. The tool is used to prioritize and steer resources toward these environmental justice communities (Alexeeff et al., 2012; Office of Environmental Health Hazard Assessment, 2017a). In the present study, the authors took a comprehensive look at the concentration of contaminants in drinking water, both individually and cumulatively, to compare potential exposure across system sizes and regions and to determine vulnerable areas and trends. Understanding which contaminants are impacting different regions and populations, as well as which areas face the highest cumulative burdens, may help focus future research and remediation efforts to those communities who potentially face the greatest risks. The authors hypothesize that smaller water systems and regions of the state that are more rural, such as the SJV, have higher levels of multiple contaminants in drinking water. Knowledge of water quality by characteristics such as system size, region, and whether a community is served by a CWS may help prioritize statewide efforts to improve water quality for areas and systems most in need.

2 | METHODS

2.1 | Selection of contaminants and violations

In California, more than 100 contaminants have drinking water standards that require routine testing and reporting to the state. This study examined 12 contaminants (names, abbreviations, units, and detection limits for reporting [DLRs] are listed in Table 1). These 12 contaminants were selected after receiving input from public workshops and key stakeholders, and final selection was based on the following criteria: (1) sufficient monitoring across water systems in California, (2) whether the contaminant had at least one violation, and (3) chronic and acute toxicity concerns. Some contaminants were also included based on input from state agencies and stakeholders, such as radium 226, 228. Lead concentrations from posttreatment sample locations, but prior to tap, were initially analyzed, as this was the best available data at the time of analysis. The authors did not include the lead results, as data on lead concentrations at the tap recently became available. Future analyses may use these new data to understand trends by region and system size. In addition, an evaluation of state violation data as an indicator of systems that experience contaminants commonly exceeding state regulatory limits was included. This study incorporated two types of regulatory violations from 2005 to 2013—the number of MCL violations for any contaminant and Total Coliform Rule (TCR) violations. The TCR governs the process of identifying microbiological contamination in water supplies that represents acute health concerns.

2.2 | Development of drinking water system service boundaries

Three methods were used to geographically assign all areas of California a representative water quality ranking. The authors first used available CWS service boundaries downloaded from the California Tracking's Water Boundary Tool (Tracking California, 2019; Wong et al., 2015). More than 80% of the 2,949 CWSs that were active at the time of analysis were available from this web-based tool. The remaining CWS boundaries were approximated using information on the location of water monitoring and the population served by the system using a geographic information system (ArcMap 10.2). To summarize water quality for populated areas outside of CWS boundaries (non-CWS areas), a 6-square-mile township grid from the Public Land Survey System was used. The 6-square-mile grid was selected instead of larger geographies to assign a

TABLE 1 List of contaminants and violations selected for this study

Contaminants and violations	Unit	Detection limit for reporting	Public health goal	Maximum contaminant level	% CWSs[d] with data	% Samples with nondetects[a]
1,2,3-Trichloropropane (1,2,3-TCP)	µg/L	0.005	0.0007	0.005[a]	68	88.4
Arsenic	µg/L	2.0	0.004	10	92	39.3
Cadmium	µg/L	1.0	0.04	5	92	99.2
1,2-Dibromo-3-chloropropane (DBCP)	µg/L	0.01	0.0017	0.2	54	67.6
Hexavalent chromium (Cr^{6+})	µg/L	1.0	0.02	10	22	39.3
Nitrate, reported as NO_3	mg/L	2.0	45	45	96	15.5
Perchlorate	µg/L	4.0	6	6	91	83.6
Radium 226, 228	pCi/L	1.0	0.05, 0.019	5	12	93.5, 96.9[c]
Total trihalomethanes (TTHMs)	µg/L	1.0[b]	—	80	86	67.5
Tetrachloroethylene (PCE)	µg/L	0.5	0.06	5	89	77.1
Trichloroethylene (TCE)	µg/L	0.5	1.7	5	89	77.0
Uranium	pCi/L	1.0	0.43	20	48	24.3
Maximum contaminant level (MCL) violations	—	—				
Total coliform rule (TCR) violations	—	—				

[a]List of detection limits for reportings can be found here: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/Chemicalcontaminants.html.
[b]Detection limit for reporting for individual TTHMs.
[c]Percentage reflects radium 226 and radium 228 separately.
[d]Community Water System.

sufficient amount of ambient groundwater monitoring data to local residents. The boundary types are summarized in Table 2. An example of the boundary types are shown in Figure 1, with established CWS boundaries and approximated CWS boundaries both shown in green and non-CWS gridded areas in orange. Nonpopulated areas of California or areas with no available groundwater monitoring data are shown with a crosshatch. Additional details on how boundaries were developed are described in a technical document (Office of Environmental Health Hazard Assessment, 2017b).

TABLE 2 Number of community water systems (CWSs) and population captured in California boundary type

Service boundary type	*n* (%)	Population (million)[a]
Established boundaries	2,443 (83.8)	35.050
Approximated boundaries	471 (16.2)	0.074
Non-CWS areas	NA	1.830
No data available	NA	0.300

Abbreviation: NA, not available.
[a]U.S. Census Bureau (2010) Census Summary File 1.

2.3 | Concentrations of chemical contaminants in CWS areas

This study focuses on drinking water intended for consumption without further treatment, here termed "delivered water." To extract water contaminant data reflective of delivered water for CWS areas, the authors used four SWRCB data sets (publicly available through request). California's Safe Drinking Water Information System (SDWIS) and its predecessor, the Permits, Inspection, Compliance, Monitoring, and Enforcement Database (PICME), which had the most complete data at the time, both contain information on the location and treatment type of chemical monitoring within a system (State Water Resources Control Board, 2018b). Water Quality Management (WQM) and the Annual Compliance Report data sets provided contaminant sampling and violation data that were linked to the first two data sets (State Water Resources Control Board, 2018a, 2018c).

Distribution systems for California CWSs vary considerably in complexity and size. For example, some CWSs provide water directly to consumers from a single source (e.g., water reservoir), some may have one treatment

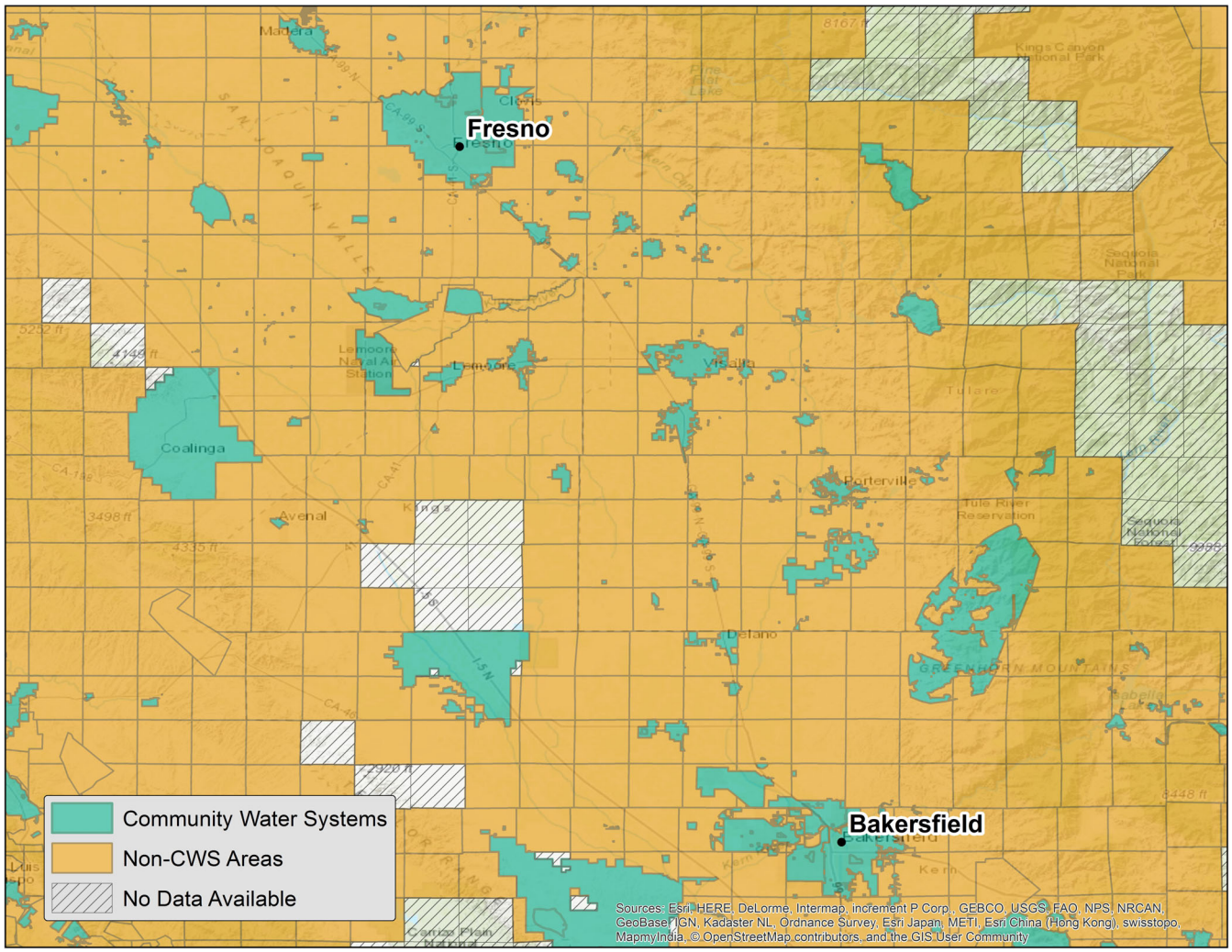


FIGURE 1 Community water system (CWS) service boundaries and noncommunity water system areas in San Joaquin Valley

plant, or larger CWSs may have multiple treatment plants serving different areas within a water system, and chemical monitoring may occur at multiple locations. The PICME and SDWIS data sets contain data that identify the type of treatment (or its absence) at each monitoring location within the distribution system. Monitoring locations identified as "active treated" (posttreatment) or "active untreated" (never to be treated) were extracted. "Raw" (pretreatment) samples were selected only when a water system did not have reported treated or untreated samples for specific contaminants. Water systems test contaminants prior to treatment (in a "raw" sample), and if the levels are below standards, they may not test posttreatment. Next, the authors extracted water quality data from the SWRCB's WQM databases for 2005–2013, reflecting the most recent three compliance periods at the time of this analysis. The 9-year compliance cycle, which contains three 3-year compliance periods, was used to maximize the number of water quality samples.

2.4 | Concentrations of chemical contaminants in non-CWS areas

In this study, Californians receiving drinking water from private wells or very small systems (fewer than 15 connections) without chemical monitoring data were assumed to drink local or ambient groundwater. To summarize ambient water quality for these non-CWS areas, raw or untreated groundwater monitoring data from WQM for any public water system were selected, including samples from non-CWSs (schools, gas stations, etc.) within the township. Groundwater samples from two databases for the years 2005–2013 were also selected: (1) the U.S. Geological Survey Priority Basins Project, which assesses groundwater used for public drinking water supplies, and (2) the SWRCB Groundwater Ambient Monitoring and Assessment Domestic Wells Project, which sampled a limited number of domestic wells for contaminants of concern on a voluntary basis in six California counties. Less than 1% of the state's population did

not have any available monitoring data within their township grid (Table 2 and Figure 1).

2.5 | Calculating contaminant concentrations by system

The following methods were used to estimate the average concentration of each contaminant in each CWS or non-CWS boundary area. For CWSs, a time-weighted average for each contaminant at each drinking water sampling location was calculated. Weights were based on the number of days between the first sampling date and the next available sample for each calendar year. As regulatory monitoring schedules for different contaminants vary, this time-weighting approach assumes that samples reflect water quality for the entire time before a subsequent test occurs for that contaminant. For non-CWS areas, samples were averaged by the calendar year without time weighting. For CWSs and non-CWSs, yearly means were averaged across the 9-year study period for each sampling location. These sampling location averages were then averaged to obtain a mean concentration for each system. Finally, the contribution of water purchased from wholesale water systems was incorporated. Concentrations were adjusted for systems that purchase water by known or default fractions (e.g., 50% purchased water) of the water that the wholesaler supplies that system. For the violation measures, the total number of violations by system was summed for the study period. To address sample test results that were below the detection limit, a value of zero or the DLR divided by a square root of 2 was used to represent nondetect results. For contaminants with less than 30% of tests below the detection limit (i.e., higher detection frequencies), the value of the detection limit divided by the square root of 2 was used (Lubin et al., 2004). For all other contaminants (i.e., low detection frequencies), concentrations listed at or below the reported detection limit were treated as zero. Nitrate and uranium were the only contaminants with less than 30% of nondetect samples. The complete list of available data and detection frequencies for each contaminant is listed in Table 1. In addition, a sensitivity analysis was conducted to see whether using zero or the detection limit divided by the square root of 2 altered results. All analyses were conducted using SAS 9.4 (SAS Institute Inc., Cary, N.C.).

2.6 | Calculating contaminant averages by region and system size

This study divided California into eight regions (Figure 2) comprising counties roughly corresponding to regional governmental bodies and adapted from a previous study (Cushing et al., 2015). Water systems were categorized into either non-CWS or CWS areas, and CWS areas were then further subdivided into sizes (small, intermediate, medium, and large) based on the number of connections suggested by the Safe Drinking Water Plan for California (Table 3; State Water Resources Control Board, 2015b).

A population-weighted approach was used to calculate the concentration of the 12 contaminants by region or system size category. Within region or system size category, the contaminant average was weighted by the number of people residing in the system or non-CWS area. The number of people residing in a system was estimated by spatially overlaying the population of census blocks, the smallest unit of the 2010 census geography, to CWSs and non-CWS (townships) boundaries (U.S. Census Bureau, 2010). If a census block included areas from two or more systems, the population was weighted based on the areal portion of the census block. As census blocks and tracts fall evenly into counties, each population assignment and associated water contaminant data were readily grouped into regions. The following equation describes the population-weighted average calculation by region and system size category.

$$\text{Population weighted average for each region or system size category} = \frac{\sum_{i=1}^{n}(C_i \times P_i)}{\sum_{i=1}^{n} P_i},$$

where P is the population associated with each block or block portion, and C is the contaminant average and total number of violations associated with each block or block portion (i=index of summation, with 1 being the lower limit or starting point of summation; n=upper limit or stopping point of summation).

2.7 | Statistical analysis by region and system size

Average contaminant concentrations were used to compare the relative level of pollution burden in drinking water across regions and system sizes. First, a Kruskal–Wallis test was used to examine for significant differences in the estimated average concentrations for each particular contaminant or violation measure by region and by system size. Second, to understand the regional burden of individual contaminants, the regional average was compared to the average concentration for the rest of the state by creating ratios. Ratios by system size categories, including the non-CWS areas, were also calculated.

FIGURE 2 Map of counties used to differentiate regions in California

TABLE 3 Water system size categories and population capture

System size category	Number of connections	Census population (%)[a]		Number of systems (%)	
Non-CWS areas	NA	2,089,616	(5.62)	NA	
Small	<200	189,362	(0.51)	1,862	(63.14)
Intermediate	200–999	731,107	(1.97)	420	(14.24)
Medium	1,000–9,999	5,268,529	(14.17)	449	(15.23)
Large	≥10,000	28,899,030	(77.73)	218	(7.39)
Total		37,177,644	(100.0)	2,949	(100.00)

Abbreviations: CWS, community water system; NA, not available.
[a]Based on 2010 U.S. Census Bureau.

$$\text{Ratio indicating regional burden} = \frac{R}{S},$$

where R is the population-weighted average of the region or system size category, and S is the population weighted average for all areas except the region or system size category.

Ratios greater than 2 were considered large enough to show a regional or system size burden, meaning the contaminant concentration for the region or system size was two times higher than for the rest of the state. In addition, this analysis was conducted for system sizes within regions. If a region had a high ratio (>2) when stratified

across all system sizes within a region, contaminants were considered to be a substantial regional burden because the high ratios were not limited to a specific system size category or limited amount of systems.

Third, to determine regions with the greatest cumulative drinking water contamination, each region was given a relative rank for each contaminant or violation measure. For example, the region with the lowest estimated average concentration of a chemical was given a rank of 1 for that chemical, and the region with the highest estimated average concentration of that chemical was given a rank of 8 (of eight regions). Similar to methodology used for the drinking water indicator in CalEnviroScreen 3.0 (Office of Environmental Health Hazard Assessment, 2017b), contaminant rankings were then summed for all chemicals and violation measures for each region, and this total was used to represent cumulative burden of contaminants and determine the region that ranked the highest in terms of cumulative contamination.

Finally, to evaluate contaminant concentration trends across water system sizes, the Jonckheere–Terpstra two-sided trend test was used to evaluate negative and positive trends. To test if there was a decreasing level of contamination as system size increased, the negative (left-sided *p*-value) trend test was conducted. The positive (right-sided *p*-value) trend test was also performed for the contaminants to test for an increasing level of contamination as system size increased. The authors ran both trend tests with and without the inclusion of non-CWS areas. Differences were considered statistically significant when *p*-values were less than .05.

3 | RESULTS

3.1 | Population for regions and system size categories

Of the 2,949 CWSs in California with service boundaries that could be obtained or estimated, 2,914 (99%) had water quality monitoring data and were included in the study sample. California's eight regions vary in total population, from 189,351 people in the Sierra Nevada to 16,743,915 people in the South Coast. Of the 2,914 systems, 1,862 are small water systems (<200 connections) and serve only 0.5% of the state's population. In contrast, the state's 218 large water systems (≥10,000 connections) serve approximately 77.7% of California's population. Population and number of systems for each region and system size category are reported in Tables 3–5.

3.2 | Regional results

There was a statistically significant difference between the eight regions for all contaminant concentrations or number of violations ($p < .0001$). Contaminant concentrations by region and contaminant are listed in Table 6. Contaminants with a regional burden, meaning the regional average was greater than twice the average for the rest of the state, are listed by region in the boxes in Figure 3, from largest to smallest ratio. The SJV had the greatest number of regional burdens (six contaminants with ratios >2), followed by the Sierra Nevada region and Northern California (Figure 3). Contaminants with ratios greater than 2, even when stratified by system size categories, are indicated with an asterisk in the boxes in Figure 3. These include TCR violations, MCL violations and 1,2-dibromo-3-chloropropane (DBCP) in the SJV, trichloroethylene (TCE) and tetrachloroethylene (PCE) in the South Coast region, perchlorate in the Desert, and radium 226, 228 in the Sierra Nevada.

The analysis on cumulative rankings by region showed that the SJV region had the highest cumulative burden of contaminants among all California regions, followed by the Desert and Central Coast. The cumulative rank score is shown in Figure 3 as a choropleth map from red (highest score) to blue (lowest score). In addition, the SJV remained the region with the highest cumulative burden when considering rankings across all sizes of CWS systems.

TABLE 4 Number of systems[a] captured within regions and system size categories

Region	Total	Small	Intermediate	Medium	Large
All of California	3,007	1,879	433	465	230
Northern California	491	348	77	62	4
Bay Area	380	252	40	49	39
Sacramento Area	203	109	39	31	24
Sierra Nevada	187	128	41	18	0
San Joaquin	669	477	88	84	20
Central Coast	378	279	44	42	13
South Coast	412	147	58	111	96
Desert	287	139	46	68	34

[a]Systems may overlap regions. Therefore, the number of systems used for each region may be higher than the total number of systems used in the study.

TABLE 5 Census-based population[a] captured within regions and system size categories

Region	Total	Non-CWS areas		Small		Intermediate		Medium		Large	
		n	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)
All of California	37,177,644	2,089,616	(5.6)	189,362	(0.5)	731,107	(2.0)	5,268,529	(14.2)	28,899,030	(77.7)
Northern California	1,047,324	343,174	(32.8)	26,640	(2.5)	66,729	(6.4)	396,374	(37.8)	214,408	(20.5)
Bay Area	7,138,472	266,814	(3.70)	25,005	(0.4)	47,286	(0.7)	614,344	(8.60)	6,185,024	(86.6)
Sacramento Area	2,307,767	326,663	(14.2)	13,241	(0.6)	37,846	(1.6)	243,035	(10.5)	1,686,982	(73.1)
Sierra Nevada	189,351	80,402	(42.5)	7,503	(4.0)	27,736	(14.6)	73,710	(38.9)	0	(0.0)
San Joaquin	3,934,365	635,804	(16.2)	55,735	(1.4)	96,267	(2.4)	870,746	(22.1)	2,275,811	(57.8)
Central Coast	1,420,588	143,280	(10.1)	19,123	(1.3)	52,937	(3.7)	430,917	(30.3)	774,332	(54.5)
South Coast	16,743,915	131,585	(0.8)	24,670	(0.1)	341,845	(2.0)	1,953,193	(11.7)	14,292,622	(85.4)
Desert	4,395,862	161,894	(3.7)	17,446	(0.4)	60,462	(1.4)	686,209	(15.6)	3,469,851	(78.9)

Abbreviation: CWS, community water system.
[a]Based on 2010 U.S. Census Bureau.

TABLE 6 Population-weighted contaminant concentrations[a] or violation averages[b] for all community water system (CWS) and non-CWS areas by California region

Contaminants	Northern California	Bay Area	Sacramento Area	Sierra Nevada	San Joaquin	Central Coast	South Coast	Desert
1,2,3-TCP—µg/L	0.00000	0.00008	0.00044	0.00000	0.00366	0.00052	0.00142	0.00326
Arsenic—µg/L	1.06	0.21	1.93	1.68	2.78	1.27	1.26	1.01
Cadmium—µg/L	0.0250	0.0030	0.0390	0.0010	0.0060	0.0300	0.0010	0.0002
DBCP—µg/L	0.176	0.004	0.027	0.097	0.018	0.021	0.001	0.011
Cr^{6+}—µg/L	2.17	3.12	3.74	0.10	1.41	1.01	2.98	2.63
Nitrate—mg/L	5.46	4.23	4.45	3.17	15.58	7.18	5.68	11.98
Perchlorate—µg/L	0.013	0.014	0.016	0.001	0.135	0.011	0.152	0.454
Radium 226, 228—pCi/L	0.01	0.13	0.00	4.37	0.16	0.22	0.09	0.26
TTHMs—µg/L	8.87	25.49	13.36	11.31	12.97	24.05	38.65	17.17
PCE—µg/L	0.06	0.01	0.01	0.01	0.05	0.09	0.28	0.19
TCE—µg/L	0.00385	0.00082	0.00375	0.00002	0.04747	0.01344	0.44074	0.07732
Uranium—pCi/L	0.86	0.80	1.20	7.12	4.22	1.81	2.87	3.59
MCL[a]	0.30	0.09	0.18	0.73	0.69	0.19	0.05	0.14
TCR[a]	0.79	0.06	0.44	1.06	2.48	0.25	0.03	0.26

Abbreviations: 1,2,3-TCP, 1,2,3-trichloropropane; Cr^{6+}, hexavalent chromium; DBCP, 1,2-dibromo-3-chloropropane; MCL, maximum contaminant level; PCE, tetrachloroethylene; TCE, trichloroethylene; TCR, Total Coliform Rule; TTHMs, trihalomethanes.
[a]Concentration averages may be underestimated as samples below the detection limit were substituted with zero or the detection limit divided by the square root of 2.
[b]Violation values represent the population-weighted average total number of violations within the region.

3.3 | Results by system size

There was a statistically significant difference between the five system sizes (non-CWS areas plus the four CWS sizes) for all contaminants and violation measures ($p < .0001$), showing that contaminant concentrations vary considerably between system size categories. Among only CWSs, small water systems (fewer than 200 connections) have the most contaminants with concentrations greater than twice the average for the rest of the state: arsenic, cadmium, uranium, MCL violations, and TCR violations (Table 7). For only CWSs, small water systems also had the highest concentration averages of arsenic, nitrate, uranium, cadmium, MCL violations,

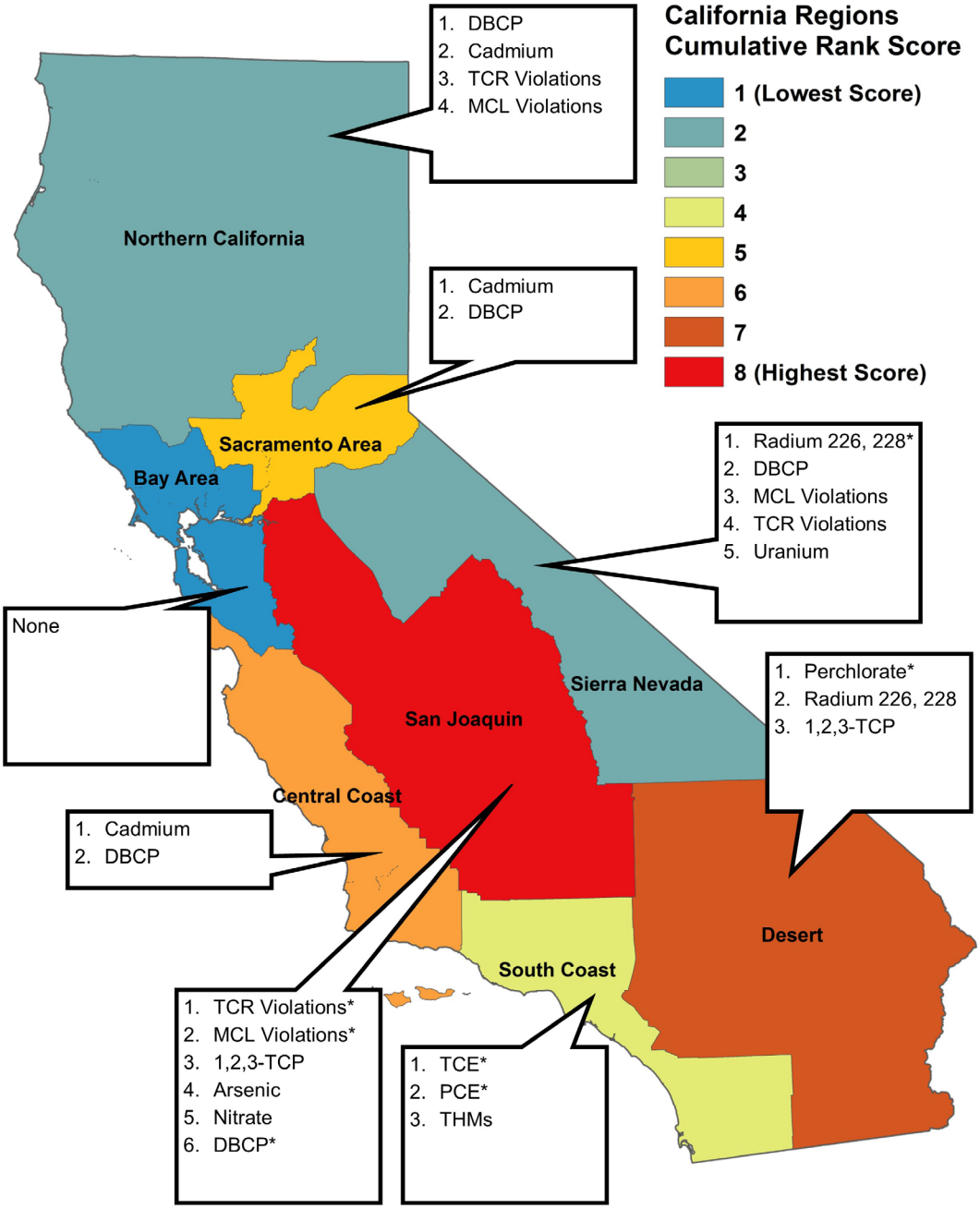


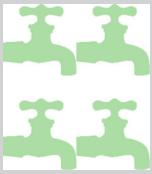
FIGURE 3 Map of cumulative rank scores in California regions shown by color. In boxes are contaminants with concentration averages (for all systems in a region) more than twice the concentration average of the rest of the state. *Contaminants with a substantial burden when the concentration is more than twice the concentration average of the rest of the state for all system sizes in a region Abbreviations: 1,2,3-TCP, 1,2,3-trichloropropane; DBCP, 1,2-dibromo-3-chloropropane; MCL, maximum contaminant level; TCR, Total Coliform Rule; TTHM, trihalomethane

and TCR violations (Table 8). Cumulatively, for all contaminants evaluated, small water systems had the highest rank, followed by medium, large, and intermediate water systems respectively. (Table 7). Large water systems were the only size not burdened by MCL and TCR violations compared with the rest of the state. However, large water systems had the highest burden (ratios) and contaminant average rank for TTHMs, TCE, and PCE compared with the smaller water systems.

Non-CWS areas in California had the highest burden of water contamination compared with regulated CWSs. Similar to small water systems, the non-CWS areas had a higher number of contaminants (5) with ratios greater than two compared with intermediate, medium, and large CWS size categories (Table 7). Californians in non-

CWS areas had the highest cumulative burden of contaminants compared with those being served by CWSs, ranking the highest in 7 of the 12 contaminants, including arsenic, nitrate, DBCP, and hexavalent chromium (Cr^{6+}) (Table 8). Regional results for non-CWS areas indicate that the average concentrations for PCE and DBCP are the highest in Northern California, and cadmium is the highest in the Central Coast. In addition, when evalu-

TABLE 7 Cumulative rank score and contaminant burden by system size

	Non-CWS area	Small (n = 1,862)	Intermediate (n = 420)	Medium (n = 449)	Large (n = 218)	Legend
Cumulative rank score by water system size						Lowest Cumulative Rank Score; Highest Cumulative Rank Score
Contaminant burden: concentration averages two times the rest of the state	Arsenic Cadmium DBCP Nitrate Radium 226, 228	Arsenic Cadmium MCL TCR Uranium	MCL Radium 226, 228 TCR	MCL TCR	TCE THMs	

Abbreviations: CWS, community water system; DBCP, 1,2-dibromo-3-chloropropane; MCL, maximum contaminant level; TCE, trichloroethylene; TCR, Total Coliform Rule; TTHMs, trihalomethanes.

TABLE 8 Region or system size category with the highest concentration average for each contaminant

	Region with the highest concentration average		System size category with the highest concentration average	
Contaminant	**CWSs only**	**Non-CWS area only**	**CWSs only**	**CWSs and non-CWS area**
1,2,3-TCP	San Joaquin	San Joaquin	Intermediate	Intermediate
Arsenic	San Joaquin	Sacramento	Small	Non-CWS area
Cadmium	Sacramento	Central Coast	Small	Non-CWS area
DBCP	San Joaquin	Northern California	Medium	Non-CWS area
Cr^{6+}	Sacramento	Sacramento	Large	Non-CWS area
Nitrate	San Joaquin	San Joaquin	Small	Non-CWS area
Perchlorate	Desert	Desert	Large	Non-CWS area
Radium 226, 228	Sierra Nevada	Sierra Nevada	Intermediate	Intermediate
TTHMs	South Coast	South Coast	Large	Large
PCE	South Coast	Northern California	Large	Large
TCE	South Coast	South Coast	Large	Large
Uranium	Sierra Nevada	South Coast	Small	Small
MCL violations[a]	Sierra Nevada	NA	Small	Small
TCR violations[a]	San Joaquin	NA	Small	Small

Abbreviations: 1,2,3-TCP, 1,2,3-trichloropropane; Cr^{6+}, hexavalent chromium; CWS, community water system; DBCP, 1,2-dibromo-3-chloropropane; MCL, maximum contaminant level; NA, not available; PCE, tetrachloroethylene; TCE, trichloroethylene; TCR, Total Coliform Rule; TTHMs, trihalomethanes.

[a]MCL and TCR violations are not assessed for non-CWS areas.

ating regional burdens in only non-CWS areas, radium 226, 228 was a significant burden in the Sierra Nevada region and 1,2,3-trichloropropane (1,2,3-TCP) in the SJV (ratios > 10) (data not shown). Overall, the Central Coast also has the highest cumulative burden of multiple contaminants in non-CWS areas only, followed by both SJV and South Coast regions (second highest rank) (data not shown).

3.4 | Trend test and patterns across the state

The trend test results indicate that system size has an effect on the concentration of certain contaminants. There was a statistically significant ($p < .05$) negative trend (as system size increased, the level of contamination decreased) for arsenic and cadmium when including both CWSs and non-CWS areas among all systems in California (Figure 4). There was also a statistically significant negative trend for MCL violations and TCR violations among CWSs. In contrast to these contaminants, trend test results indicated that TCE and TTHM levels increased as system size increased. When only CWSs were included in the positive trend test, perchlorate and PCE also showed a statistically significant trend (Figure 5). In Figures 4 and 5, the contaminant concentration averages were scaled from 0 to 10 by assigning the maximum concentration a score of 10.

While some contaminants did not show a significant trend or burden, they showed notable patterns (Figure 6). DBCP appears to primarily be an issue for non-CWS areas in the Northern California region. However, when examining only CWSs, the SJV has the highest concentrations (Table 8). Results for nitrate and uranium indicate that a disproportionate level of contamination mainly occurs in small water systems compared with large water systems. These patterns, along with the trend test results by system size, can be observed through a heat map table (Figure 6). Regional contaminant concentration averages and system size averages are included in Data S1 (Supporting Information).

4 | DISCUSSION

In this study, the authors developed a novel method that takes a large amount of water quality monitoring data and characterizes potential exposure to drinking water contaminants for all areas of the state, including those on private wells or small, unregulated systems. The authors overcame limitations associated with linking water

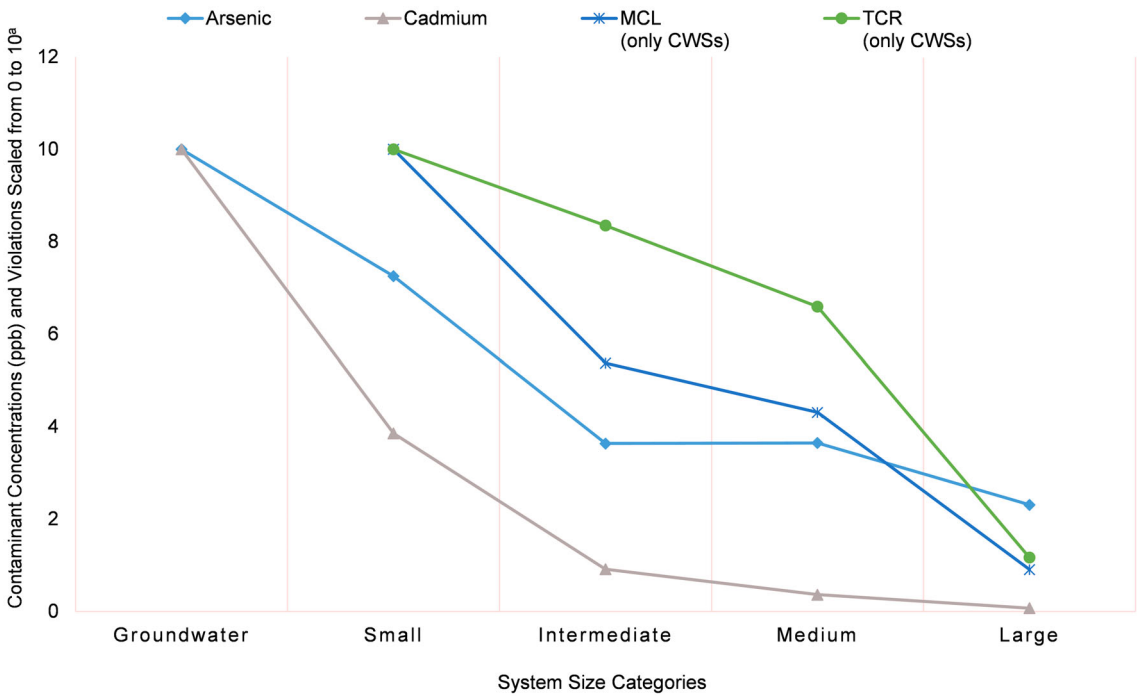


FIGURE 4 Contaminants with statistically significant negative trends ($p < .05$) across system size categories. [a]Contaminant concentration and violation averages have been scaled from 0 to 10 by assigning the maximum concentration a score of 10. Abbreviations: CWS, community water system; MCL, maximum contaminant level; TCR, Total Coliform Rule

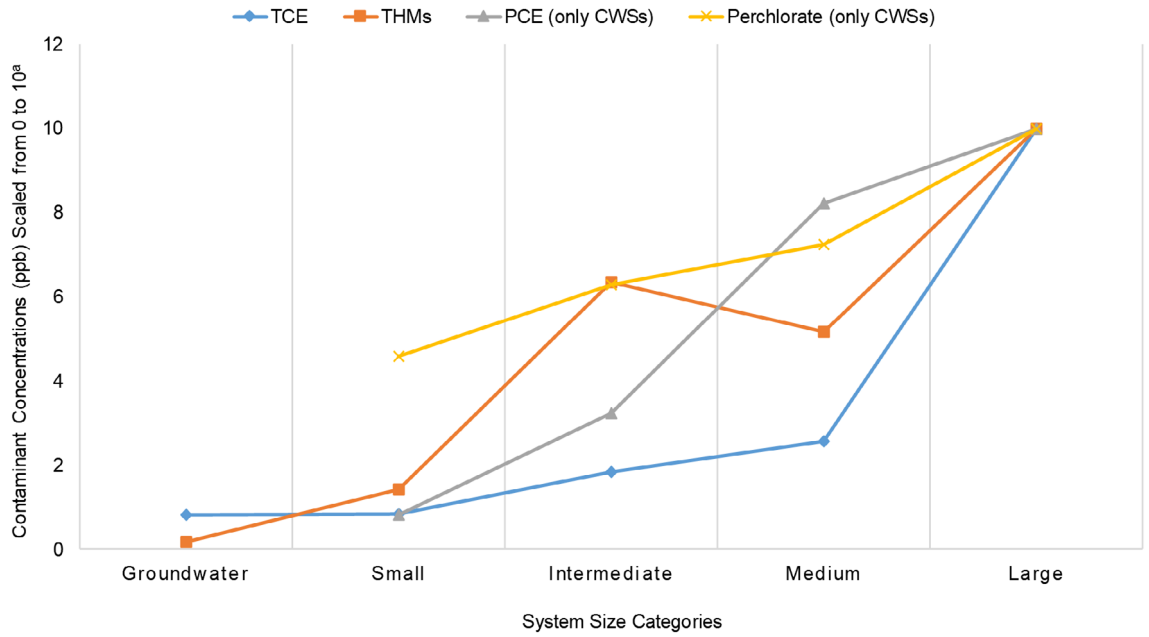


FIGURE 5 Contaminants with statistically significant positive trends ($p < .05$) across system size categories. [a]Contaminant concentration averages have been scaled from 0 to 10 by assigning the maximum concentration a score of 10. Abbreviations: CWS, community water system; MCL, maximum contaminant level; TCR, Total Coliform Rule

quality data to multiple geographic boundaries across all of California. This is the first study to use or develop a full set of drinking water system service boundaries in its analysis. Previous studies have examined contaminated water for a limited number of individual contaminants regionally or only for CWSs or did not use CWS service boundaries. This study used a novel metric of cumulative exposure to evaluate multiple contaminants statewide by system size and type, including areas not served by CWSs.

The findings confirm that water quality varies significantly throughout the state and provides a first screening look at regions and system sizes that are affected differently by specific and cumulative contaminants. As most water systems in California comply with standards and considering the large-scale use of regional averages, regional contaminant concentration averages were much lower than the MCL standards. Even so, regional concentrations were frequently higher than health-based PHGs for several contaminants such as arsenic, Cr^{6+}, and 1,2,3-TCP. Smaller systems had higher concentrations of multiple contaminants and violations. Results of regions or system size categories that have substantially higher single or multiple contaminant burdens can provide a useful step to address specific contaminants in areas most in need for pollution reduction.

Previous studies of California's SJV concerning high levels of arsenic, uranium, and nitrates (Balazs et al., 2011, 2012; Dubrovsky et al., 2010; Lockhart et al., 2013; Thiros et al., 2015) are supported by this study. In addition to these contaminants, the present study found this region to have the greatest cumulative burden of multiple contaminants, ranked as the highest region in the state for concentrations of arsenic, DBCP, nitrate, 1,2,3-TCP, MCL violations, and TCR violations, especially among smaller water systems. In this analysis of non-CWS areas in the SJV, concentrations of nitrate, uranium, and 1,2,3-TCP appeared disproportionately high. It is clear from the results of this study, which corroborate previous findings, that the SJV should be a continued focus of resources and further studies to examine and improve the quality of drinking water, particularly for small and disadvantaged communities in the region.

While previous studies have mainly focused on rural areas of the state such as the SJV, which bears a high burden of drinking water contamination, less research has focused on understanding and comparing contaminants in drinking water across other California regions, including urban areas. For example, in the South Coast region, which contains the Los Angeles metropolitan area, two industrial contaminants (TCE and PCE) and TTHMs (disinfection byproducts) are identified as a substantial burden. Perchlorate has the most significant burden for the Desert region, and radium 226, 228 is most significant in the Sierra Nevada region. DBCP, a pesticide banned in 1979, remains a significant contaminant burden to those relying on ambient groundwater in Northern California.

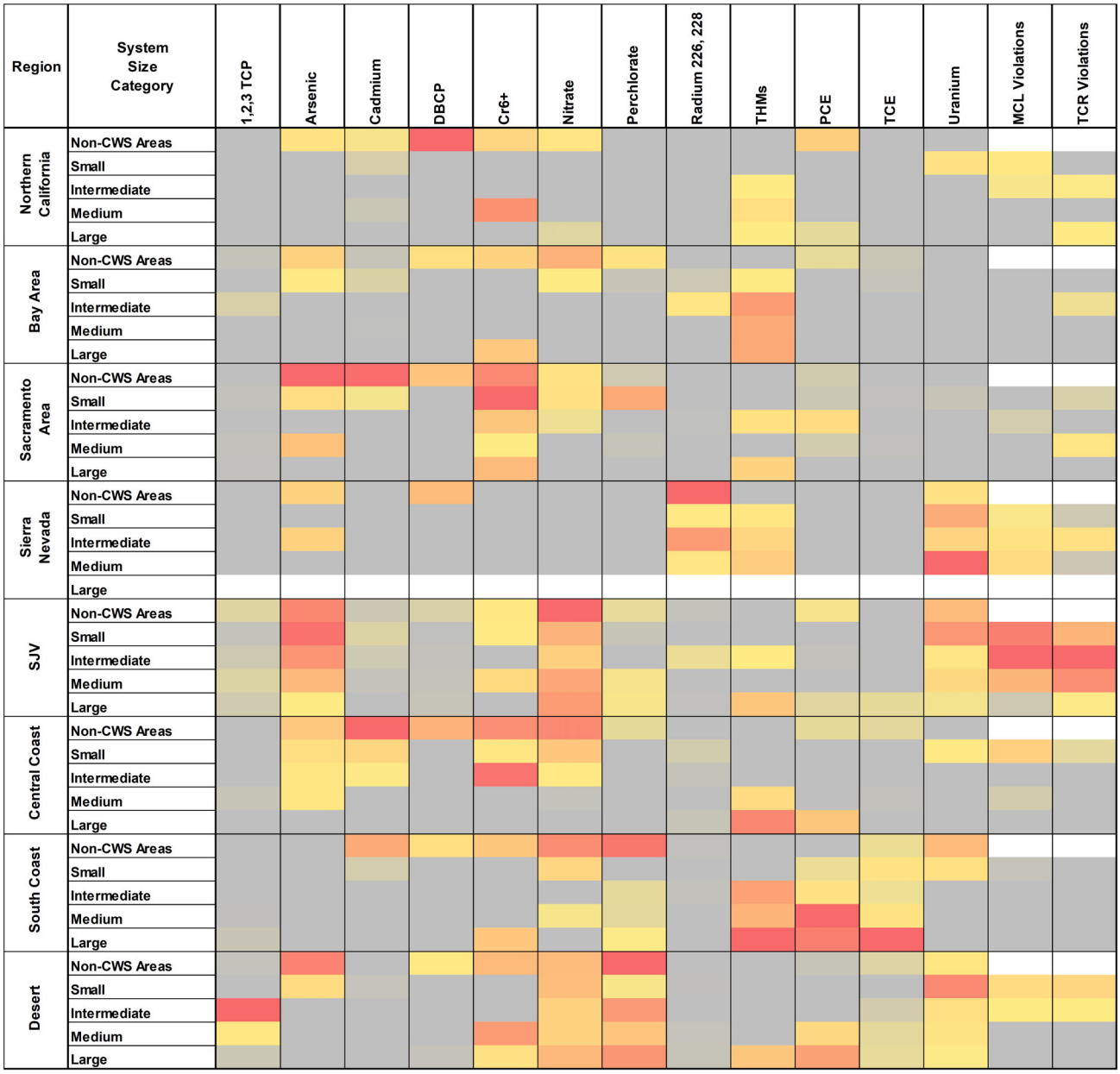


FIGURE 6 Heat map showing contaminant average concentrations by system size and region. The lowest 25% of concentrations are grayed out. Darkest red indicates highest concentrations. Abbreviations: 1,2,3-TCP, 1,2,3-trichloropropane; Cr^{6+}, hexavalent chromium; CWS, community water system; DBCP, 1,2-dibromo-3-chloropropane; MCL, maximum contaminant level; PCE, tetrachloroethylene; SJV, San Joaquin Valley; TCE, trichloroethylene; TCR, Total Coliform Rule; TTHMs, trihalomethanes

Results in this study also show that higher detections of some contaminants, such as perchlorate, are isolated by region, while others such as DBCP are more constant across the state. The results can be used to identify research and treatment efforts regionally for specific contaminants.

The results from this study demonstrating that smaller systems tend to have more MCL and TCR violations are also supported by previous research (Allaire et al., 2018; London et al., 2018; Marcillo & Krometis, 2019; State Water Resources Control Board, 2015b; Wallsten & Kosec, 2005). The present study found that small systems have significantly higher concentrations of arsenic and cadmium compared with larger systems, which indicates further efforts should focus on small water systems in California.

A significant trend for nitrate concentrations as a function of system size was not found, although small systems had higher concentrations of nitrate compared with most larger water system categories. This aligns with previous research findings that small water systems

are more vulnerable to higher nitrate levels in the SJV and nationally (Balazs et al., 2011; Schaider et al., 2019). On the contrary, the present study showed a significant positive trend for TTHMs as systems get larger, suggesting that the potential for TTHM exposure is greater for people served by large systems. This is not surprising as TTHMs are a byproduct of water chlorination treatment, which is more heavily used by large systems. PCE and TCE also showed positive trends, which may be due to greater industrial influence in more populated areas of Southern California served by large water systems. Perchlorate also showed a positive trend by system size and warrants further evaluation.

Although this study is one of the first, to the authors' knowledge, to investigate potential exposure to contaminants in drinking water across multiple regions in California, across system sizes, and for multiple contaminants, the methods used here have several limitations for use in screening-level exposure assessment. The methods for assigning water quality to geographic areas were limited by availability and accuracy of data, such as using approximated water system boundaries and townships to assign water quality to certain areas of the state. However, the boundaries for 80% of CWSs in California extracted from the Water Boundary Tool represented the most complete and accurate set of boundaries available at the time of analysis.

The monitoring databases are compiled from data reported to the state by water systems, and there are limitations in both the testing and reporting for contaminants. Data gaps and nonstandardized reporting requirements may have influenced these results, with inconsistencies in contaminant reporting cycles and some water systems receiving monitoring waivers. Although the authors made a significant effort to determine a water system's contribution of local groundwater versus imported surface water, the final mixture is likely to vary between seasons and from year to year. Due to the lack of statewide data on blending of water sources within a water system, this analysis also assumes that water quality is homogeneous within a CWS or non-CWS area. This may potentially affect larger water systems with multiple treatment plants by overestimating their contaminant averages. Data on the level of contaminants in the final blend of water delivered to consumers is not directly available, so the authors characterized delivered drinking water using monitoring data from treatment plant sampling points. For the non-CWS areas of the state, the authors recognize some of the assumptions in using public supply wells to characterize domestic well use. These include differences in well depth, which may influence water quality. However, the authors used the best available data at the time of analysis. The reliance on the various databases used in this study highlights the importance of accessible and accurate state drinking water monitoring data.

It should also be noted that the authors treated nondetect test results from the monitoring samples as concentrations of zero for all contaminants except uranium and nitrate, which had much higher percentages of detected contaminant levels. The authors acknowledge that these decisions, along with the inherent nature of environmental monitoring data with very high frequencies of nondetected values, may have a significant impact on the calculation of system-wide contaminant average concentrations (Helsel, 2006). Results of the sensitivity analysis conducted to determine whether the substitution value affects results showed that average concentrations increase as the substitution value for samples below the detection limit increases. The magnitude of change increases for contaminants as their number of nondetects increases. However, regardless of the substitution value used, significant differences between regions and system sizes, ranking of average concentrations, and trend test outcomes remained the same. Furthermore, input from experts in the drinking water field indicated that replacing nondetect results with zeroes was preferable to assuming a quantified presence of contaminant in a water system when no evidence of that contaminant existed. Many of the contaminants have detection limits that are greater than the PHG, and estimating a value above the PHG for nondetected results could unfairly highlight a public health problem in water systems when one does not exist. The authors believed it appropriate to replace nitrate and uranium nondetect samples with the DLR divided by the square root of 2 under the assumption that much higher detection frequencies indicate a greater likelihood of these two contaminants throughout the state. The authors' intent in designing this study was to examine differences in levels of contaminants between systems in various regions and system sizes and not to treat our average contaminant concentrations as true values of exposure to California residents. Assumptions and limitations on how best to represent nondetected results in environmental monitoring data are widely discussed in the literature, and the authors concluded that the methods relied upon were appropriate to characterize and compare water quality across California water systems for the purpose of this analysis.

While providing useful information on potential exposures from drinking water contaminants, the results are of the greatest use in screening scenarios to identify and compare relative burdens of exposure and to understand areas for continued research. Further efforts are needed to assess detailed and direct exposure to contaminants, which could involve biomonitoring and a focus on

smaller geographic units or even individual water systems. A large-scale analysis comparing water quality between systems of different sizes that serve mainly groundwater versus surface water could be an important step in understanding the importance of source water type with respect to contamination concerns. Further studies could examine other factors, such as socioeconomic disparities and water system capacity, that are associated with variations in water quality throughout the state. Additional challenges faced by small water systems may include the technical, managerial, and financial capacity of a water system's operations, which may also be related to higher levels of contaminants. In 2012, California passed Assembly Bill 685, which legislatively recognizes that all Californians have the right to safe, clean, affordable, and accessible drinking water. California is currently taking steps to evaluate and address the human right to water, and continued work to address the gap in water quality between small and large systems has been identified as a priority and is supported by this study's findings.

5 | CONCLUSION

As a screening-level exposure assessment, this study is one of the first to examine multiple drinking water contaminants that may be a potential problem in specific regions across California and by different system sizes, including areas not served by public water systems. The summarized regional and system size contaminant averages were all below MCL standards; therefore, results presented here cannot be used to draw conclusions about drinking water safety but instead may provide a preliminary snapshot of areas with poorer water quality that could help target localized investigation and treatment efforts throughout California. Key findings include a potential high burden of MCL and TCR violations, 1,2,3-TCP, arsenic, and nitrate in the SJV; DBCP in Northern California groundwater; and TCE, PCE, and TTHMs in the South Coast region and among large water systems. Overall, Californians residing in areas outside of regulated public water systems (non-CWS areas), served by small water public water systems, and people living in the SJV have the greatest burden of exposure to multiple drinking water contaminants. Future analyses could explore socioeconomic factors associated with drinking water contamination in specific regions or system size categories. As access to improved data becomes available, and technology improvements yield more sensitive and affordable testing protocols, the ability to characterize drinking water quality by water system, linking boundaries to monitoring data, and comparing potential exposures at both a local and state-wide level will be vitally important for government agencies and researchers concerned with public health.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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